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Review article

A review on hydraulic fracturing of unconventional reservoir

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ABSTRACT

Hydraulic fracturing is widely accepted and applied to improve the gas recovery in unconventional reservoirs. Unconventional reservoirs to be addressed here are with very low permeability, complicated geological settings and in-situ stress field etc. All of these make the hydraulic fracturing process a challenging task. In order to effectively and economically recover gas from such reservoirs, the initiation and propagation of hydraulic fracturing in the heterogeneous fractured/porous media under such complicated conditions should be mastered. In this paper, some issues related to hydraulic fracturing have been reviewed, including the experimental study, field study and numerical simulation. Finally the existing problems that need to be solved on the subject of hydraulic fracturing have been proposed.

1. Background

Unconventional gas mainly includes shale gas, tight gas and coal seam gas. Shale gas is commonly in mudstone, shale and between them the interlayers of sandstone. Tight gas often has been stored in tight sandstone or sometimes limestone. Coal bed methane is contained within coal seams. Their common attribute is that the permeability of the matrix is very low, and the permeability often has been improved by artificial or natural fractures [55]. However, the differences between them are also significant. For example, the effective shale thickness for gas production should be more than 15 m while the height of coal is generally from 0.6 m to 5.0 m [68], as coal seams to be fractured may be multiple and thin, hydraulic fracturing in coal needs to be more accurately designed and controlled. Moreover, the Young's modulus of coal is smaller than shale and tight sandstone, the permeability of coal is more sensitive to stress due to the development of cleat system, and leakoff in coal may be more severe, which can significantly affect the fracturing result. Due to the complexity of unconventional reservoirs, it is challenging to predict the initiation and propagation of hydraulic fractures [39]. For example, the complex in situ stress state and distribution of rocks of varied attributes, which may change the profile of hydraulic fractures [38]; the existence of arbitrary pre-existing interfaces may diversify or arrest hydraulic fractures [93]; the temperature effect [75]; the fluid loss and transport of proppant; the competition between hydraulic fractures, and its recession and closure [4]. Thus, it is crucial to explore how hydraulic fracturing process will happen in complex geological settings.

Firsthand materials of hydraulic fracturing come from in-door experiments, and field study. Laboratory study undergoes from small-scale rock samples with several cubic centimetres to large ones with one cubic metre or more. Since it is easy to control the stress conditions and make artificial structures within samples, hydraulic fracturing process with different stress field and rock structures can be conveniently studied. Especially in large scale experiments, it is possible to build a full size borehole, or to control the development of hydraulic fractures, and the hydraulic fracture geometries can be obtained easier and parametric study can be quite handy [7,41].

Field study is much more complex because the mechanical traits and geologic conditions and in-situ stress fields are different and unique while laboratory experiments can be

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controlled and repeated, and difficulties for hydraulic fracturing can be easily added by in situ experiences [87]. Many methods can be used to evaluate hydraulic fracturing in field study. For example, historical production data such as bottomhole pressure and near-wellbore pressure losses can be used to understand the fracturing process [45]; sonic anisotropy and radioactive tracer logs can be used to analyse hydraulic fracture geometry [76]; and both resistivity and acoustic imaging can be used to evaluate dominant fracture azimuths and borehole features [44].

2. Influences of in-situ stresses on hydraulic fracturing

In order to optimize gas production in shale, it is necessary to create as much contact area between the unconventional gas reservoir and fracture system as possible, within economical permit. Stress condition in formation is a dominating factor in creating hydraulic fractures at different locations and being able to control their propagation [51]. Warpinski and Teufel [87] showed from field results that in-situ stress was the overriding factor that influenced the fracture propagation when it was in a high-stress region compared to interfaces, modulus, strength changes, fluid pressure gradients, and most bedding planes. Near wellbore stress condition can control the initiation and propagation of hydraulic fracture, and the size of hydraulic fracture and injected fluid can also change the stress field in the reservoir. Also the real time change along the near wellbore can change the hydraulic fracture direction and affect the production greatly [3,9,90]. The differences in far-field principal stress can alter the direction of hydraulic fractures and also determine whether there is a main fracture or there are many secondary fractures, as well as the shape of fracture has also been constrained [23,88]. But Abass et al. [2] pointed out that the near wellbore stress field can control the hydraulic fracturing in its early stage, and once the fracture extended into the original stress field, its propagation will be controlled by the original stress field. Thus, the well should be perforated to bypass the near wellbore stress field in order to create oriented fractures perpendicular, angularly or longitudinal to the wellbore, as shown in Fig. 1.

Stress difference not only influences the direction of hydraulic fractures, but also the quantity. Zhou et al. [96] found that within the scope of high horizontal stress difference, hydraulic fracture was a dominating fracture with random multiple branches, while within the scope of low horizontal stress difference the hydraulic fracture was partly vertical, planar fracture with branches. Moreover, they related the pressure profile to natural network conditions. For example, a high frequency of pressure

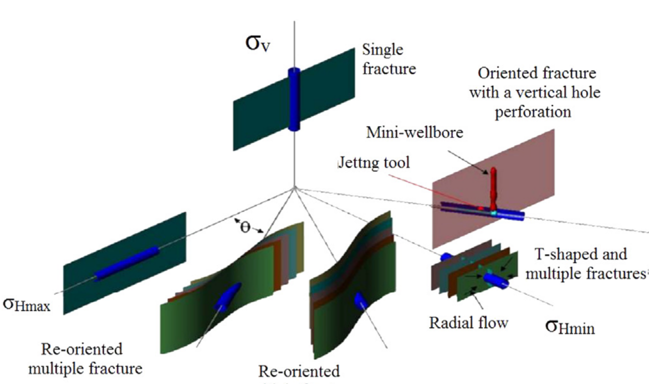

Fig. 1. Fracture geometry with different wellbore orientations relative to in-situ stress field [2].

fluctuation during fracture propagation could mean the existence of small natural fractures while the smooth pressure could mean the existence of natural fractures with strong network. Stress field will be changed during or after hydraulic fracturing process, thus, hydraulic fractures may mutually affect each other. Rabaa [30] found that because the stress field was changed after the fracture was created, subsequent created fracture would be affected by the new stress field and would not be parallel to the first fracture. Moreover, stress field with other factors, such as fluid viscosity and flow rate, may be together affect hydraulic fracturing process. For example Weijers et al. [89], experimented on hydraulic fractures induced from horizontal wellbores. They found that transverse fractures happened with low flow rate, viscosity and high horizontal stress contrast, while axial fracture initiated with higher flow rate and viscosity. Especially, multiple fractures occurred when the wellbore was oblique to the preferred plan.

The intersection angle between in-situ stress and wellbore direction directly affects the orientation of hydraulic fracture, and due to the geological structure and stress condition, the expected initiation and propagation of hydraulic fracture will reversely determine the spacing of wells and fractures, and orientation of wells [49,57]. Thus, in order to effectively perforate strata and develop dominant fractures and maximize fracture complexity, it is important to master the stress condition in the reservoir and also know how it will evolve with hydraulic fracturing process [14,52]. However, the initiation locations of hydraulic fractures are usually equally spaced, which is a waste of fracturing capital because the formation is heterogeneous [73]. Thus, in order to properly select locations for hydraulic fractures, factors such as near wellbore stress condition, wellbore direction, direction of principal stress etc. should be considered with cautious [21]. Horizontal well is popular in unconventional gas stimulation because it can greatly increase the contact area between fracture and reservoir. Experiments on horizontal wells from Ref. [1] showed that hydraulic fracturing was significantly influenced by its deviate angle from the direction of maximum horizontal stress. They found that the initiation pressure was related to the angle; if the angle was not 0, crack would be reorientated into the direction perpendicular to the minimum in-situ stress, during which shear failure would occur but followed immediately by tensile failure; if the angle is 45°, multiple parallel fractures happened, which would cause screenouts and high treating pressure; besides, T-shaped crack would be generated due to the near wellbore stress field if the overburden stress was the highest among the three principal in-situ stresses.

In shale gas reservoirs horizontal wells that can reach 1600 m long are predominant [12,26], multiple hydraulic fractures are placed along horizontal wells and multi-stage fracture often has been performed [18]. Earth deformation is significant because of the leakoff, anelastic deformation, enlarged fracture width when hydraulic fracturing has been performed in a large area, or residual fracture width is common after hydraulic fracturing due to rough fracture surface and/or sliding [86]. Stages of hydraulic fracturing process will be performed on a single well or on multiple wells, moreover, simultaneous and sequential fracking has been adopted to lead the orientation of hydraulic fracture [13,85]. Previous hydraulic fractures impacts on later fracking work and simultaneous fracking will influence each other by reforming the stress field and transfiguring the formation [46,64,88]. Different spacing will lead to different stress condition which can prevent/enhance secondary hydraulic fractures [88]. Moreover, contact area between hydraulic fracture and rock matrix has been enlarged by increase the fracture complexity or networking [59,66]. Even in some cases, bottomhole pressures were varied between zones, and this difference could impact on in-situ stress profiles and affect the fracture propagation [46]. However, the complex geological structure and stress condition is unable to be reproduced in in-door experiment. Thus, the numerical methods are effective tools for figuring out the mechanisms of hydraulic fracturing in intricate geological setting.

3. Influences of complex geological structures on hydraulic fracturing

(1) Effects of heterogeneities of rocks

Heterogeneities of rocks also have an impact on hydraulic fracturing, such as the variation of rock properties including the permeability, porosity and Young's modulus [53]. Fluctuations of averaged porosity and permeability may be intense due to the range and position of selected area [40]. As shown in Fig. 2, in the experiments of [40]; debonded grains were found in the front of fracture, but in the grains micro-cracks also had been created but insufficient to breakdown the grain. However, if the compaction stress was large enough, grains would be crashed in front of the fracture. Moreover, under compressive stress state, the deboned and/or crashed grains could repack into tighter and less porous configuration around the fracture tip, which changed the regional porosity and permeability, as well as the stress condition that dominated the propagation of fracturing. Also, the permeability of faults could be strongly affected by in-situ stress magnitudes and orientation [10], thus, it is important to trace the variation of stress-permeability during hydraulic fracturing process, but now it can only be evaluated after the fracking is finished [44].

The contrast between rocks may also influence hydraulic fracturing. The layered composite of most sedimentary formation require the study of the extension of hydraulic fractures in heterogeneous rocks [54]. Teufel and Clark [81] found that the elastic properties of either side of the interface could influence the propagation of vertical growth by affecting the vertical distribution of the minimum horizontal stress state, because the increase in minimum horizontal in-situ stress in the bounding layers and a weak interfacial shear strength of the layers could contain vertical growth of hydraulic fractures. For composite rock, differences in Young's Moduli and the fluid volume within the fracture and the conductivity and productivity in adjacent layers can influence the width of hydraulic fracture if it grows across the interfaces [28,79]. The first is layers of higher strength may be micro-cracked for they take more stress; yielding in soft rock that dissipates the energy can also contain the fracture or cause discontinuous fractures; interface slip may retain the hydraulic fracture or deviate the path, as shown in [86] (Fig. 3).

It is common that rock exhibits elastic-brittle behaviour, but sometimes the rock for hydraulic fracturing is not in elastic-brittle. For example [19], did a series of both small and large scale tests on particular rocks. Three kinds of fracture fronts had been observed. They were round, bevelled and fingered, as shown in Fig. 4. It was observed that cavity expansion was firstly occurred before the injection pressure reaches its peak, then hydraulic fracture initiated from the expanding cavity near the pressure peak, and finally it propagated after the pressure peak. Boundary instability also had been observed in small scale tests, and plastic deformation and compressive stress state were important to hydraulic fracturing.

Density also can influence hydraulic fracturing process. Hanson et al. [42] researched on the effects of elastic modulus, friction coefficient of the interface and density of the rock sample on hydraulic fracturing geometry based on unbounded interface tests. They concluded that lowering the friction on the surface of pre-existing fracture had a similar effect on lowering the elastic modulus of the rock on the opposite side of the pre-existing fracture. They also concluded that a change in elastic modulus across the interface had a greater effect than a change in density.

(2) Pre-existing fracture

In field, natural fractures although several feet far from the widespread hydraulic fracture would open or slip due to hydraulic fracturing process [86], and the hydraulic fracture could transvers a large pre-existing weak plane, or be arrested by the plane, or grow along an end of the plane. Moreover, deviated wellbore often produces non-planar fracture [1], reorientation and interaction between fractures [61].

Lamont and Jessen [54] found that hydraulic fracture was capable of extending across pre-existing fractures of varying width and orientation, but it also depended on the direction of least-compressive stress and location of pre-existing fracture. Moreover, the width of the pre-existing fracture would not prevent hydraulic fracture if fluid flow had been injected enough. Daneshy et al. [27] attributed the effects of pre-existing fractures to its influence on local stress field. Their experiments showed

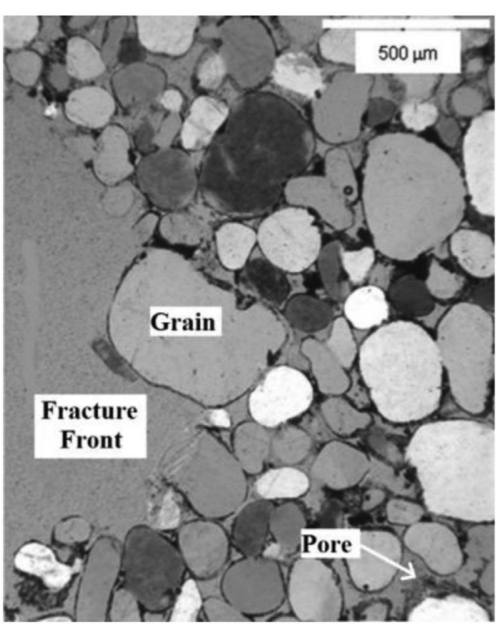

Fig. 2. Pore-scale fracture front in sandstone [40].

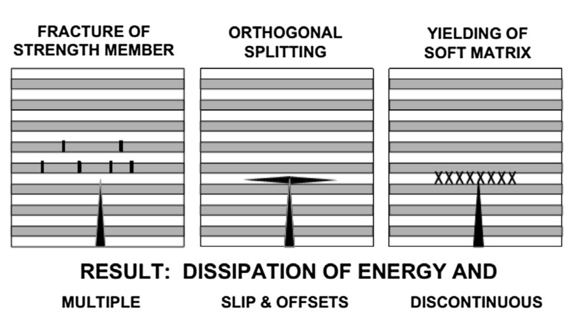

Fig. 3. Composite behaviour for height growth [86].

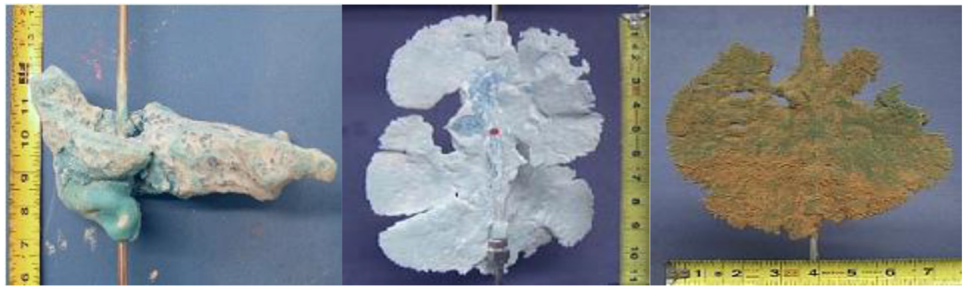

Fig. 4. Fracture profiles in different types of particulate materials: (a) mixture of fine sand of silica flour; (b) silica flour; (c) Georgia Red Clay [19].

that comparatively small flaws, whether open or closed, were very locally influenced induced hydraulic fracture, and were unable to change their overall orientation. But the hydraulic fracture could transvers a large pre-existing weak plane, or be arrested by the plane, or grow along an end of the plane. The size of pre-existing fracture is not the only reason that may affect hydraulic fracturing process. Blanton [11] showed that only under high differential stresses and high angles of approach hydraulic induced fractures would cross pre-existing fractures. In most of their tests the hydraulic fractures were either diverted or arrested by the pre-existing fractures. The results implicated that in the field hydraulic fractures were more likely to have diverted wings at different angles or have truncated wings of different lengths.

The open or close state of small pre-exiting fractures, such as fissures, micro-cracks, is important for production because they can change the regional properties of reservoir [22,36]. Gale et al. [33] studied the natural fractures in the Barnett shale. It is found that the natural fractures distributed in a power-law size mode and the largest fracture would stay in open state. The open fracture could on one hand prevent the propagation of hydraulic fracture, and on other hand contribute to the flow network that connected to the wellbore. A group of natural fracture often performed a high anisotropy that depends on their linkage to hydraulic fractures, and if they were connected to water, they could be detrimental. The evolvement of the fractures around the main fracture would increase the regional permeability, but it also could lead to significant leakoff, which could limit the development of hydraulic fracture. However, it is hard to determine whether these fractures are in open state and stay as viable flowpaths [47,72]. The key factor that can blunt the fracture propagation is shear sliding along the interface [28] and Anderson et al. [6] found that if the frictional properties changed along the interfacial surface close to hydraulic fracture, the path of the fracture could be alerted. In their experiment, the hydraulic fracture could also be impeded by the opposite surface of the intersected interface. Warpinski and Teufel [87] showed the field results of the influence of geologic discontinuities on hydraulic fracture propagation from mineback observations at shallow depth. They observed that hydraulic fracture could penetrate into joints through the interface, while often terminate near faults, and the orientation was often changed when they succeeded to propagate across the faults. They also observed that hydraulic fracture was terminated at a parting plane but with a small length of propagate, and the reason was that the friction was enough to reinitiate the fracture on the other side but there was not sufficient transmitted stress to let it propagate easily in the higher stress layer.

In some situations, natural fracture may be filled with different kinds of minerals, which forms a combination and the strength of the combination may have an influence on hydraulic fracturing process. Casas et al. [17] studied hydraulic fracturing process with different bond strength of pre-exiting fractures. They used epoxy and grout to fill in interfaces within the rock sample to make artificial joints which had different stiffness. They found that the epoxy joint with a lower stiffness than the rock sample arrested hydraulic fracture while the grout joint with a higher stiffness than the rock sample did not stop the fracture crossover.

4. Numerical methods for hydraulic fracturing modeling

Hydraulic fracturing basically involves three processes: (1) the deformation of fracture surfaces; (2) the fluid flow within the fracture; (3) the fracture propagation [4,43]. Linear elasticity is usually used as the deformation law of rock; power law fluid is set for the fluid within the fracture; linear elasticity fracture mechanics theory is usually adopted as the propagation law; an additional term is often given to the fluid flow equation to calculate the leakoff effects [4,15].

The theoretical models of hydraulic fracturing have been developed for more than half a century. The classic hydraulic fracturing 2D models contain PKN model [65,70] and KGD model [34,50]. Green and Sneddon [35] studied the problem of a flat elliptic crack under constant loading. PKN is applicable when fracture length is much larger than the height, because it assumes a plain strain in vertical direction [65,70]; while KGD model assumes the crack width in horizontal is independent of its vertical position, thus, it is only reasonable when the height is much greater than its length [34,50]. In order to investigate the fracture propagation with different height, Pseudo-3D (P3D) models have been developed based on PKN models. Mainly, there are two categories in P3D modes: one is cell-based models in which fracture has been divided into several self-similar cells along horizontal direction [32,78]. Another is known as ‘lumped model’, which assumes a fracture consists of two half ellipses of equal lateral extent but different vertical extent [24]. However, these models cannot simulate fracturing with arbitrary shape, and palaeo stress would be regionally inversed in some field, which would cause widespread horizontal micro-cracks, and excess leakoff and fissure pressure storage would make pseudo-3D models and linear-elasticity inappropriate [45]. Thus, PLanar 3D (PL3D) models have been developed [5,78]. In PL3D models, fracture and the coupled fluid are simulated either moving triangular mesh [5,25], or fixed rectangular mesh [8,77]. PL3D assumes that the shape of hydraulic fracture is arbitrary and can be represented by a Green's function [77]. But it requires a consistency condition between layers [5], and cannot simulate ‘out of plane’ fractures [15], and the use of Green's function makes it not easy for nonlinear or anisotropic rocks [71]. Thus, fully 3D model is in need to simulate hydraulic fracturing process.

In order to simulate the real time fracturing process and avoid singularity problems in classic fracture mechanics, cohesive element method, which is implemented by FEM and pre-assumes a fracture zone, has been developed by using traction-separation law the singularity problem in crack tip [20]. Width of fracture shrinks to zero at the tip of fracture due to the corresponding energy dissipation, namely, no separation in front of the fracture [16] and lubrication theory often is adopted to simulate the fluid flow within fracture [20]. Although this method is capable of simulating real time crack growth [93], the fracture path is predefined by pre-installing cohesive elements, thus, it cannot predict the fracture orientation under complex stress condition, such as reorientation.

Another method is to implement FEM with continuum damage mechanics, in which the fracture is represented by the continuum element whose strength is reduced to a minimal value, and the permeability of cracked elements can be related to the corresponding strain or stress state [84]. Or a scalar damage variable related to strain can be used to represent the isotropic damage extent of continuum rock, and crack closure process was simulated by recovering the elastic moduli of rock [91]. This method is capable of simulating non-planar or ‘out of plane’ effects [56], however, the elements should be very small in order to precisely predict the path and shape of HF, and the one first order scalar damage index cannot represent the anisotropic damage for a single element, which can be solved by introducing more damage indices with higher orders [63]. Actually, the geometric choice of crack modelling depends on the its size compared to the micro-structure of rock, to the overall structure, the crack initiation, propagation, and local behaviour in crack zone [71]. Adaptive mesh strategy could be used to increase the accuracy and create reasonable mesh distribution [67].

Multi-layers formation is common in unconventional reservoir, however, when it is been numerically simulated, the layers often has been assumed as perfectly bonded together, especially when using FEM [5]. Based on PL3D model [5], used FEM to study hydraulic fracturing in multi-layered medium. But they assumed that the multi-layers formation was perfectly bonded together, slip or detach would not occur, and the rocks are homogeneous within each layer. To improve the precision without much cost in calculation [97], introduced a method to divide elements to completely fractured, fracture front, unfractured element. For fracture front element, fluid pressure was weighted by the pressure of completely fractured elements and intact elements. But by this method the profile of the fracture is roughly predicted, and the permeability and stress variation cannot be simulated accurately. Besides, Weibull's statistical model often has been used to simulate the anisotropic characteristics of rock [91], however, by using this method, the behaviour of the interface between materials cannot be considered. In order to simulate the interface attributes [31], introduced a joint model that was capable of considering opening, closing shear deformation and sliding in natural fracture system. They also used Finite Volume Method (FVM) to simulate fluid flow combined with FEM modelling reservoir deformation. The drawback is that the crack could only grow along element edges, and an interpolation strategy was implemented to generate compatible meshes between FVM and FEM by splitting nodes to create new fractures. There are some other methods that are capable of simulate the interface behaviour. For example [38], used Displacement Discontinuity Method (DDM) to model vertically propagating hydraulic fracture penetrates into upper and lower bedding plane considering interfacial slip based on P3D model and they concluded that when the slip occurs at the top or bottom interfaces connected to a hydraulic fracture, width deformation was easier than the slip happened in the interface that arrested the leading edge of the crack. Another method is Boundary Element Method (BEM). By using BEM [94], concluded that friction behaviour on the pre-existing interface was important and the widths of fracture on the two faces of the pre-existing fracture were different because there was an energy loss due to friction; soft rock was more possible to pinch the fracture propagation than stiff rock and large stress difference between layers could slow the fracturing process [95], etc. However, it could be seen that when there were several layers of rocks, it became harder to solve the problem by using BEM or DDM, because apply continuity conditions on the bond between rocks the solution becomes complex and will severely restricts the problem size [69].

Other methods that have been used to simulate hydraulic fracturing process of hydraulic fractures include eXtended Finite Element Method (XFEM), Discrete Element Method (DEM) and Discrete Fracture Network (DFN). Taleghani et al. [80] used XFEM to investigate the hydraulic fracture intersecting a single natural fracture [48]; implemented it on the effects of intersection angles between hydraulic fractures and natural fractures. However, there are still many tough bones for this method, such as the branching and intersection of fractures, fluid flow related to fractures, and the heterogeneities of rocks that may bring solution problem, etc. [71]. Zhang et al. [92] used DEM to investigate hydraulic fracture process with different rates of fluid injection into granular media in pore-scale. The pore space was defined by the domain within closed chains of particles, and pore throat was defined at the two connected domains. At different injection rates, the movement of particles were different, thus, different hydraulic fractures would be formed. Same method had been used in the research of Thallak et al. [82]. They studied the simultaneous hydraulic fracturing process by injection at two points. It was found that the two hydraulic fractures would change the local stress field, and the propagation of hydraulic fracture would be dominated by local stress field but far field stress. However, it is hard of DEM is to consider the continuum attributes of rock, such as Young's Modulus, permeability; especially when it comes to field scale problem, the calculation cost of DEM is very large. Tsang et al. [83] used DFN to simulate micro-fractures to study the hydromechanics of samples with full developed natural fractures; and Meyer et al. [62] simulated the complex natural fracture system in macro-scale based on DFN. By DFN, it is able to consider fluid flow and fracture mechanics within the fracture, however, the attributes of matrix has often been simplified and cannot be accurately simulated, neither the generation of new fractures can be properly considered, and there is also limitations on the angle between fractures [29,58,60].

5. Conclusion

Hydraulic fracturing is an essential stimulation method in unconventional reservoirs. The operation cost for a hydraulic fractured well can reach millions of dollars and the benefits from better understanding and controling this technology are obvious. Under complex geological settings, it is important but hard to predict how the hydraulic fracturing will evolve and it should be controlled with caution, because hydraulic fractures always cover a large scope and meet different rocks and structures, and endure various stress conditions. Undesirable hydraulic fracturing results will not only cause economic lost but also lead to environment pollution, such as water contaminant caused by the hydraulic fracture penetrating into groundwater layer, which is harmful for ecosystem and is always a public concern. Thus, it is important to understand the mechanisms of hydraulic fracturing with complex geological structures and stress conditions.

Because of the low permeability in unconventional gas reservoir, hydraulic fracturing is applied to generate the fracture and their networks to improve gas recovery. In order to create a suitable fracture system, many parameters need to be optimized, such as the number of perforation clusters per stage, the spacing between stages, the length of the horizontal well, the sequence of fracturing operations etc. However, hydraulic fracturing in unconventional reservoir is more complex than the conventional one, and it is affected by many factors, such as the low porosity/permeability, complex in situ stress state, the distribution of rocks of varied attributes and the existence of arbitrary pre-existing interfaces etc. Especially when multiple hydraulic fractures have been performed, the competition between hydraulic fractures will also influence hydraulic fracturing process. The limitation in the knowledge on the mechanisms of hydraulic fracturing in complex geological setting has restricted the invention and application of innovative stimulation methods, such as Zipper Fracturing [74]. Based on the literature review as above, here are some problems that still need to be further studied for unconventional gas reservoir:

(1) Stress is a dominating factor that influences hydraulic fracturing process. Most of the existing numerical studies of hydraulic fracturing have been performed on simplified stress condition that cannot reflect the complex stress distribution in unconventional gas reservoirs. Moreover, stress is changing during the hydraulic fracturing process, and its variation is sometimes significantly dominates the subsequent hydraulic fracturing process. Also stress will be influenced by geological settings, such as different rock materials, natural fractures etc. Thus, it is necessary to keep track on the real time stress variations in order to optimize hydraulic fracturing operation through numerical simulations in this project.

(2) Heterogeneity is common and significant in unconventional reservoirs, including the heterogeneous properties of rock, such as Young's modulus, compression/tensile strength of multiple materials, porosity, permeability etc. and the geological structures such as interlayers and pre-existing fractures which are more complicated than the conventional one. In an unconventional reservoir, these factors interact with each other and thus should be studied in a coupling relation between stress-porosity-permeability etc. Moreover, some characteristics need to be specially considered for unconventional reservoir, for example, fluid flow in unconventional reservoir may obey different flow laws etc.

(3) Multistage hydraulic fracturing has been performed in unconventional reservoir, but the optimization of the treatment is still under discussion because the mutual effect of hydraulic fractures is complex especially when considering the heterogeneities in unconventional reservoir. Hydraulic fracturing not only will change the stress condition but also will change the geological structures by changing their open/close state or create secondary fractures from them. Nevertheless, existing numerical simulations seldom have conducted the research on the bases of complex geological setting considering the heterogeneity of reservoir and real time stress variation during the fracturing process, which is vital for the optimization of hydraulic fracturing design.

(4) Hydraulic fracturing has been performed on multiple wells with simultaneous/sequential performing method. New methods such as Zipper Fracturing have been performed based on multiple well fracturing methods to create complex fracture system to increase production. However, it is still unclear on the mechanisms of hydraulic fracturing performed on multiple wells, including the mutual effect of hydraulic fractures considering the complex geological settings, and it becomes a great restriction on innovative simulation methods. Moreover, the operation of production well will also change the stress and fluid flow distribution, and will affect the hydraulic fracturing process. Thus, it is necessary to study hydraulic fracturing process on multiple wells to figure out the mechanisms of fracturing process and optimize hydraulic fracturing performance.

(5) Although numerous laboratory studies have been conducted on hydraulic fracturing, few numerical studies have been performed on the experiments to further analyse the mechanisms of hydraulic fracturing on the particular conditions under complex geological settings and further address the above issues.

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